Interferometry for ELITE

David I. Robertson* and William M. Folkner†

*Max-Planck-Institut für Quantenoptik, Callinstraße-38, D-30167, Germany
†Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract. The purpose of the interferometry in the ELITE mission is to measure the differential displacement between the two inertial sensors mounted in the spacecraft. It will thus provide an independent verification of the performance of the inertial sensors. The interferometric system should function under all the likely operating modes of the inertial sensors. In one likely mode all the suspension forces in one of the sensors would be switched off and the sensor allowed to drift freely over perhaps 10s of microns.

Here we present a system to achieve this measurement and give some of the constraints on the laser performance and spacecraft environment that must be satisfied in order to provide a useful measurement.

INTRODUCTION

LISA is a proposed space mission to measure gravitational waves with frequencies from $10^{-4}\,Hz$ to $1\,Hz$. It requires significant advances in the performance of a number of technologies such as: inertial sensors, low frequency laser interferometry and drag-free satellite operations using field emission ion thrusters. The ELITE [1,2] mission is proposed as a low cost flight to test these key technologies. Its aim is to demonstrate their operation at a level close to the final LISA requirements. The LISA mission is outlined by Danzmann in these proceedings [3] and in more detail in [4].

The payload of the ELITE microsatellite will consist of two inertial sensors, with laser interferometry to measure their separation. The spacecraft will be maintained in a drag-free orbit by using the signals from the sensors to control proportional ion thrusters.

The two inertial sensors are mounted in a ULE plate. This plate also serves as a high stability optical bench with all optical components mounted on the bench.

The laser used to illuminate the interferometer is a Nd:YAG laser similar in design to that proposed for the LISA mission and is described in [5]. The laser is mounted away from the optical bench and the light is brought to the bench by a single mode optical fibre.

INTERFEROMETER LAYOUT

The interferometry for the ELITE mission should measure the relative displacement of the two inertial sensors to a level of a few $\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at frequencies above 1 mHz and thus confirm that the sensors are indeed inertial to this level of accuracy. This will also verify the techniques required to do low frequency laser interferometry between inertial masses for the LISA mission.

A schematic of the optical layout is shown in Fig. 1. Light from the laser is introduced onto the optical bench by the optical fibre. Some of this light is phase modulated by an electro-optic modulator (*eom*) and then introduced to an reference cavity. The laser is frequency stabilised to this cavity using reflection locking. The remaining light is split into two paths. In the measurement path the light is frequency shifted by about 80 MHz in an acousto-optic modulator (*aom*) and is then reflected from the two inertial masses before being recombined with light from the reference path at a beamsplitter. In the reference path the light is frequency shifted by a second *aom* by 80.01 MHz and is then recombined at the beamsplitter. Thus at the photodiode we have a beat signal at 10 kHz. The phase of this signal varies with changes in the length of the measurement

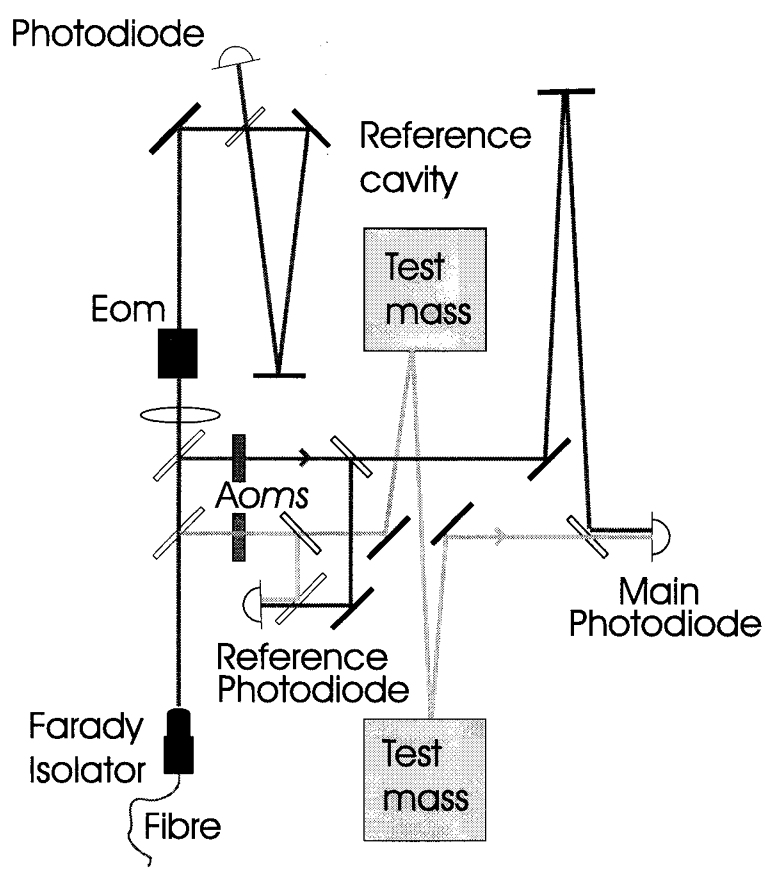

FIGURE 1. A schematic diagram of the ELITE optical layout. The measurement path is shown in gray and the reference path in black.

path. To achieve a measurement accuracy of $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ we need to measure the phase of this 10 kHz signal with an accuracy of $6 \times 10^{-5}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$.

INTERFEROMETER REQUIREMENTS

A number of different noise sources could couple in to the measurement of the relative displacement of the two inertial sensors δx. Here we consider the most important noise sources and derive the constraints they imposed on the spacecraft and its systems.

Laser Frequency Noise

If there is a path length difference of Δx between the measurement path and the reference path then laser frequency noise will couple directly to the measurement of δx.

$$\delta\nu \leq 9 \times 10^4 \left(\frac{3\,\mathrm{mm}}{\Delta x}\right) \left(\frac{\delta x}{1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}}\right) \mathrm{Hz}/\sqrt{\mathrm{Hz}} \tag{1}$$

This, in turn imposes a constraint on the stability of the reference cavity (see equation 3).

Laser Power Noise

The laser power P reflected from the inertial sensors (each of mass m) produces a force on the masses. Fluctuations δP in the laser power will produce fluctuating accelerations on the inertial sensors which could limit the sensitivity of the measurement. For 1 mW of light in the measurement arm we get a required laser power stability at a Fourier frequency of 10^{-3} Hz of:

$$\frac{\delta P}{P} \leq 1.2 \times 10^{-4} \left(\frac{1\,\mathrm{mW}}{P}\right) \left(\frac{m}{0.4\,\mathrm{kg}}\right) \left(\frac{\delta x}{1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}}\right) /\sqrt{\mathrm{Hz}} \tag{2}$$

This requirement can be satisfied by existing Nd:YAG lasers [5].

Thermal Stability

Temperature changes on the optical bench can produce spurious signals by a number of different routes, including direct effects on the inertial sensors. Here we consider only influences on the interferometry.

Reference Cavity

The length stability of the reference cavity could limit the frequency stability of the laser. Using the frequency stability requirement from equation 1 and a thermal expansion coefficient of α we get:

$$\delta T \leq 1 \times 10^{-2} \left(\frac{3 \times 10^{-8}/\mathrm{K}}{\alpha}\right) \left(\frac{\delta x}{1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}}\right) \mathrm{K}/\sqrt{\mathrm{Hz}} \tag{3}$$

Path Length Changes

The measurement accuracy could be degraded by thermally driven changes of the distances on the optical bench that differentially affect the two arms of the interferometer. For an optical path of length L in each arm and assuming that the difference in temperature fluctuations between the two beam paths is a factor of β below the absolute fluctuations, the relevant formula is:

$$\delta T \leq 7 \times 10^{-4} \left(\frac{3 \times 10^{-8}/\mathrm{K}}{\alpha}\right) \left(\frac{0.5\mathrm{m}}{L}\right) \left(\frac{\beta}{10}\right) \left(\frac{\delta x}{1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}}\right) \mathrm{K}/\sqrt{\mathrm{Hz}} \tag{4}$$

Optical Thickness Changes

A number of optical elements are used in transmission. The optical thickness of these elements will be temperature dependent, both through refractive index changes and physical thermal expansion. Taking a combined coefficient of α and an optical thickness of d then we get:

$$\delta T \leq 3 \times 10^{-4} \left(\frac{1 \times 10^{-5}/\mathrm{K}}{\alpha}\right) \left(\frac{5\mathrm{mm}}{d}\right) \left(\frac{\beta}{10}\right) \left(\frac{\delta x}{1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}}\right) \mathrm{K}/\sqrt{\mathrm{Hz}} \tag{5}$$

The relevant paths in equations 4, 5 are from the beamsplitter in front of the reference photodiode to the beamsplitter in front of the main photodiode down the reference arm and down the measurement arm.

CONCLUSIONS

We have presented an interferometry scheme to measure the differential displacements between the inertial sensors in the ELITE spacecraft. The system has been designed to minimise the effect of thermally driven changes in the optical path length, however these still impose a temperature stability requirement of $\sim 3 \times 10^{-4}\mathrm{K}/\sqrt{\mathrm{Hz}}$ at a frequency of 10^{-3} Hz. Further modelling of the spacecraft is required to see if this stability can be achieved.

ACKNOWLEDGMENTS

We would like to thank our colleagues in the ELITE science team, particularly those in Hannover, Glasgow and Garching, for much helpful advice. The work described in this paper was in part carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

REFERENCES

1. Jafry Y., *ELITE: European LISA Technology Demonstration Satellite*, these proceedings.
2. Danzmann K.,*ELITE Proposal*, RAL, Didcot, 1998.
3. Danzmann K.,*LISA and ground-based detectors: An overview*, these proceedings.
4. Bender P., *et al.*, *LISA Pre-Phase A Report, (Second edition)*, Garching: MPQ, **MPQ 233** 1998.
5. Peterseim M., *et al.*, *Laser system for ELITE*, these proceedings.